Characteristics of the $21/2^+$ isomer in ^{93}Mo: toward the possibility of enhanced nuclear isomer decay

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Abstract

To discuss whether an enhanced isomer decay is a preferred process in a plasma environment it is required to know the structure of the isomer as well as the nearby states. The spin-21/2, 6.85-hour high-spin isomer in ^{93}Mo is investigated within a shell model which well describes nuclei in this mass region. By using the obtained wave-functions which correctly reproduce the observed $B(E2)$, $B(E4)$, and $B(M1)$ transitions, characteristics of the isomer are shown in comparison with the isomeric states in neighboring nuclei. Calculations suggest that these high-spin isomers are formed with almost pure single-particle-like configurations. The ^{93}Mo $21/2^+$ isomer has the predominant configuration $\pi(g_{9/2})^2_8 \otimes \nu d_{5/2}$ lying below the $15/2^+$, $17/2^+$, and $19/2^+$ states due to neutron-proton interaction, which is the physical origin of its long lifetime. The key $E2$ transition that connects the $21/2^+$ isomer to the upper $17/2^+$ level is predicted to be substantial (3.5 W.u), and therefore there is a real prospect for observing induced isomer deexcitation.

Key words: High spin isomer, Enhanced isomer decay, Nuclear shell model
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Long-lived nuclear isomeric states have been the focus of recent discussions [1,2]. Nuclear isomeric states may play important roles in nucleosynthesis in

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stars [3]. For the ^{93}Mo $21/2^+$ isomer ($E_x = 2.425$ MeV, $\tau = 6.85$ h), the lifetime variation of nuclear levels in a plasma environment [4] and possible isomeric triggering via nuclear excitation by electron capture (NEEC) [5,6] have been suggested. In a hot dense plasma, either laser heated or of astrophysical sites, nuclei in an isomeric state may have a decay rate different from the laboratory value because indirect decay channels may be opened if there exist nuclear levels lying above the isomeric level that may be excited from the isomeric state, and then decay down to the ground state.

It has been found experimentally [7] that ^{93}Mo and the other odd-mass nuclei around it systematically have high-spin isomers (the $21/2^+$ isomer and others). It is qualitatively understood that high-spin isomers in the nuclei near shell closure appear when neutron number and/or proton number is odd, namely, when the number of valence neutrons outside the $N = 50$ closed shell is one or three and/or proton number is $Z = 40$ plus one or three. Although in the present case the proton number $Z = 40$ is a semi-magic number, a few protons near $Z = 40$ seem to play a leading role in the formation of isomeric structure. Thus a few valence protons and neutrons outside a magic or semi-magic shell participate in the construction of the isomeric states in and near ^{93}Mo. The purpose of the present Letter is to show characteristics of the isomeric states, especially for the $21/2^+$ isomer in ^{93}Mo. Understanding this isomer and its possible decay channels is important for the suggested enhanced isomer decay [4,5,6]. For some key transition probabilities, especially the one that links the $21/2^+$ isomer to the upper-lying $17/2^+$ state, there has been so far no experimental measurement or theoretical calculation available. The discussion of lifetimes of ^{93}Mo in hot dense plasmas was based on an assumption for the unknown transition rate [4].

To obtain a quantitative understanding of the isomer decay, shell model calculations that can give detailed information about the microscopic insight of the states are much desired. Good effective interactions generally applicable to this mass region are needed. Ref. [8] employed an effective interaction derived by monopole corrections of the realistic G matrix and studied the low-lying spectra of Zr isotopes. There was an early shell-model study [9] for nuclei with $A = 92 - 98$ including ^{93}Mo. This article, however, focused on the discussion of the truncation scheme of spherical shell model, but did not investigate the structure and electromagnetic properties of the isomeric state $21/2^+$ and other high-spin states in ^{93}Mo. So far, knowledge of these states that is decisive in the isomer studies in a plasma environment has not been attained. Electromagnetic transition properties related to the $21/2^+$ isomer in ^{93}Mo have not been investigated. Recently, an extended $P + QQ$ interaction with monopole corrections [10,11] has been applied to interpret new experimental data of ^{94}Mo and ^{95}Mo [12]. The model reproduces well the observed level scheme up to quite high spins in ^{94,95}Mo. The shell model parameters are determined so as to consistently reproduce overall energy levels of the $40 \leq Z \leq 42$ and

$50 \leq N \leq 53$ nuclei. The region covers the nuclei around ^{93}Mo which are the targets of the present Letter. This shell model, therefore, provides an appropriate tool for our purpose.

The model is outlined as follows; for detail, readers are referred to Ref. [12]. For a general consideration we take 8 orbits ($f_{5/2}$, $p_{1/2}$, $g_{9/2}$, $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $g_{7/2}$, $h_{11/2}$) outside ^{64}Ge as the valence space, with fixed single-particle energy (all in MeV) $\varepsilon_{f5/2} = -0.85$, $\varepsilon_{p1/2} = 0.0$, $\varepsilon_{g9/2} = 1.90$, $\varepsilon_{d5/2} = 4.20$, $\varepsilon_{s1/2} = 6.06$, $\varepsilon_{d3/2} = 6.63$, $\varepsilon_{g7/2} = 6.70$, $\varepsilon_{h11/2} = 7.90$. In the present calculation we restrict the model space so that valence protons act in the orbits ($p_{1/2}$, $g_{9/2}$, $d_{5/2}$) and valence neutrons in ($d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $g_{7/2}$, $h_{11/2}$). One must notice that the proton-hole orbit $f_{5/2}$ and the neutron-hole orbits ($f_{5/2}, p_{1/2}, g_{9/2}$) change the *particle* energies, and therefore have effects on calculated results.

The shell model code NuShellX [13] is employed. For the interactions, mass (A) dependent force strengths for the $J = 0$ and $J = 2$ pairing forces, quadrupole-quadrupole (QQ) force, octupole-octupole (OO) force are respectively fixed as follows: $g_0 = 25/A$, $g_2 = 260/A^{5/3}$, $\chi_2 = 300/A^{5/3}$, $\chi_3 = 200/A^6$ for the pp terms; $g_0 = 20/A$, $g_2 = 260/A^{5/3}$, $\chi_2 = 200/A^{5/3}$, $\chi_3 = 200/A^6$ for the nn and np terms. Here, we use the same force strengths for the nn and np interactions in order to reduce the number of parameters. Moreover, we add two monopole corrections to the proton interactions, $\Delta k^{T=1}(p^{\pi}_{1/2}, p^{\pi}_{1/2}) = -0.45$ and $\Delta k^{T=1}(g^{\pi}_{9/2}, g^{\pi}_{9/2}) = -0.25$ in MeV.

Calculated energy levels for ^{93}Mo are shown in Fig. 1, which are compared with the experimental data taken from the evaluated nuclear structure data file [14]. It can be seen that the present calculation not only reproduces well the energy levels of the yrast states, but also lays the non-yrast positive- and negative-parity states at correct energies. The model describes the essential condition for the $21/2^+_1$ state to be an isomer because the lower spin $15/2^+_1$, $17/2^+_1$, and $19/2^+_1$ states all lie above the $21/2^+_1$ state, and therefore, the maximum spin below the $21/2^+_1$ state is $J^{\pi} = 13/2^+$. Multiplicities in electromagnetic decay of the $21/2^+_1$ state are therefore $J \geq 4$; namely, the most probable decay of the $21/2^+_1$ state is an $E4$ transition to the $13/2^+_1$ state. The calculation also correctly predicts that the nearest positive-parity level above the $21/2^+_1$ state is the $17/2^+_1$ state, although the calculated energy difference is a bit larger than the observed one (5 keV). The experimental level at 2.247 MeV between $13/2^+_1$ and $21/2^+_1$ was temporarily assigned as $11/2^+$ while our model predicts the second $11/2^+$ state at the corresponding energy. However, if the state observed at 2.247 MeV would be the yrast $11/2^+_1$ state, our model fails to reproduce the inverse order of the $11/2^+$ and $13/2^+$ levels. Except for this uncertainty, the successful calculation allows us to discuss the structure of ^{93}Mo.

In Table 1, we show the main components of wave-functions for the yrast states in ^{93}Mo with spin $J^+ \leq 21/2^+$. Leading configurations in these states

are given by $\pi(p_{1/2}, g_{9/2}, d_{5/2})^4[J_p^+] \otimes \nu d_{5/2}$, in which we specify configurations of four protons by spin-parity J_p^+. Table 1 clearly shows that the structure change in the positive-parity yrast states is caused by the change in proton configurations. The $21/2^+$ isomer is almost in the configuration $\pi[8^+] \otimes \nu d_{5/2}$, 92% of which is $\pi(g_{9/2})^2_{J=8} \otimes \nu d_{5/2}$. The main configuration of the $17/2_1^+$ state (lifetime 3.53 ns) has 59.1% in $\pi(g_{9/2})^2_{J=6} \otimes \nu d_{5/2}$ and 26.7% in $\pi(g_{9/2})^2_{J=8} \otimes \nu d_{5/2}$. Thus the main structure of these two isomeric states is of a rather simple single-particle configuration $\pi(g_{9/2})^2 \otimes \nu d_{5/2}$. Specifically, the $21/2^+$ isomer is formed with the fully aligned spin of two $g_{9/2}$ protons and one neutron, which characterizes a high-spin isomer.

Lifetimes of the isomeric states depend on the reduced electromagnetic transition probabilities and energy spacings from the lower states. The $21/2^+$ isomer decays to the $13/2_1^+$ state by an $E4$ transition with the largest probability. The $17/2_1^+$ state can decay to the $21/2_1^+$ state by an $E2$ transition but the energy difference (5 keV) is too small, and hence it decays mainly to the $13/2_1^+$ state

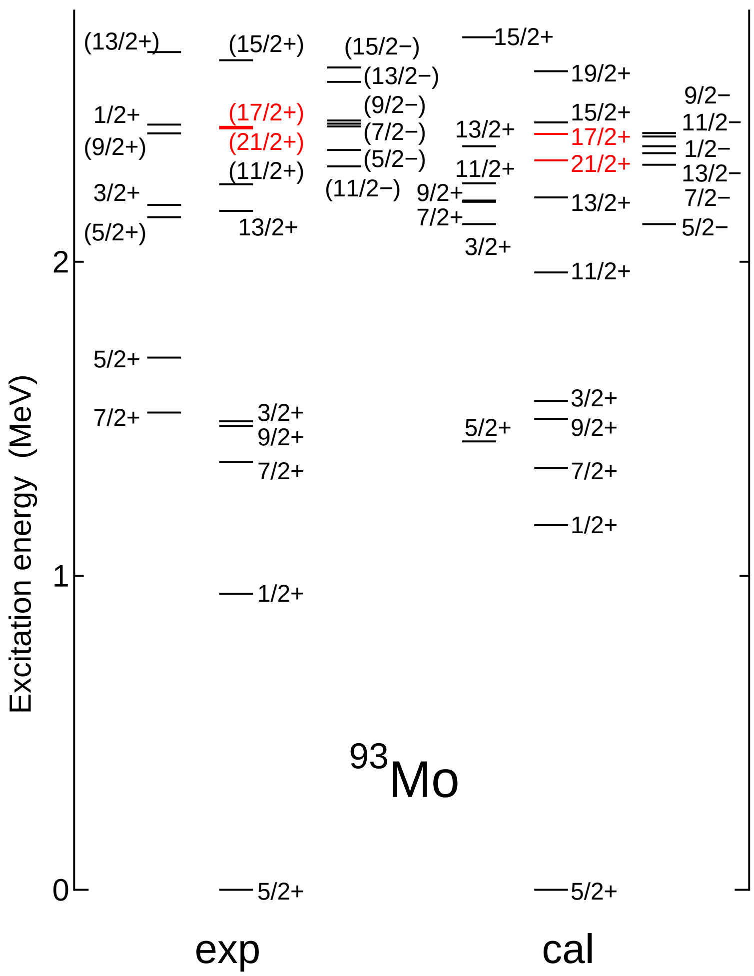

Fig. 1. (Color online) Calculated energy levels of ^{93}Mo, which are compared with experimental data taken from Ref. [14].

by an $E2$ transition. On the other hand, the $21/2^+$ and $17/2^+$ isomeric states cannot take a course of $M1$ decay because the $19/2^+_1$ ($15/2^+_1$) level lies above the $21/2^+_1$ ($17/2^+_1$) level.

Around ^{93}Mo, the nuclei with odd-number neutrons ^{91}Zr, ^{95}Ru, and ^{97}Ru have also a $21/2^+_1$ isomer (with lifetimes 4.35 μs, 10.05 ns, and 7.8 ns, respectively). ^{95}Ru has another isomeric state $17/2^+_1$ with lifetime 3.05 ns. We have carried out shell model calculations for these nuclei with the same calculation conditions. The results show that the isomeric states $21/2^+_1$ and $17/2^+_1$ in these nuclei all have the single-particle configuration $\pi(g_{9/2})^2 \otimes \nu d_{5/2}$ as the main component, as those in ^{93}Mo. However, the most significant difference of these nuclei from ^{93}Mo is that the $17/2^+_1$ level lies below the $21/2^+_1$ level. Therefore, lifetime of the $21/2^+_1$ state in ^{91}Zr, ^{95}Ru, and ^{97}Ru is much shorter than that in ^{93}Mo.

It has been experimentally known that the nuclei with odd-number protons, ^{91}Nb and ^{93}Tc, have also a $21/2^+$ isomer, with lifetime 0.92 ns and 1.72 ns, respectively. ^{93}Tc is the isotone of ^{93}Mo which can be created from ^{93}Mo by changing a neutron into a proton. In another odd-proton nucleus, ^{93}Nb, $21/2^+$ isomer has not been observed while calculations predicted its existence [15]. For a deeper understanding of the $21/2^+$ isomer, it is interesting to compare the one in ^{93}Mo with that in ^{93}Tc, which is now calculated with the same shell

Table 1
Structure of the yrast states in ^{93}Mo. Only the leading configurations $\pi(p_{1/2}, g_{9/2}, d_{5/2})^4[J_p^+] \otimes \nu d_{5/2}$ are shown, with J_p^+ denoting the spin of four valence protons. The squared amplitudes (in percent) for each J_p^+ are given.

yrast	spin of four valence protons				
state	0^+	2^+	4^+	6^+	8^+
$5/2^+$	92.5	5.9			
$1/2^+$	51.4	47.1			
$7/2^+$		89.5	8.0		
$9/2^+$		88.2	8.6	1.1	
$3/2^+$	9.2	88.0	1.4		
$11/2^+$			9.4	12.8	74.8
$13/2^+$			34.8	23.1	39.3
$21/2^+$					99.5
$17/2^+$				67.1	29.2
$15/2^+$				40.6	56.8
$19/2^+$					98.8

model.

Figure 2 shows experimental and calculated energy levels for ^{93}Tc. One sees that the model describes well the observed levels also for this odd-proton nucleus. It reproduces the order of the positive-parity yrast states and also other positive- and negative-parity states. The theory lays correctly the $17/2^+_1$ level below the $21/2^+_1$ state but the $19/2^+_1$ (and $15/2^+_1$) level above the $21/2^+_1$ state. This condition prohibits the decay of the $21/2^+_1$ state to the $19/2^+_1$ state by $E2$ or $M1$ transitions but allows only a decay to the $17/2^+_1$ state by $E2$ transition. We can thus understand some retardation in the decay of the $21/2^+_1$ state in ^{93}Tc.

What structure does the isomeric state $21/2^+$ have in ^{93}Tc? In the present model, the ^{93}Tc nucleus has no valence neutron, and therefore the states are generally described by the configuration with five protons $\pi(p_{1/2}, g_{9/2}, d_{5/2})^5[J^+]$.

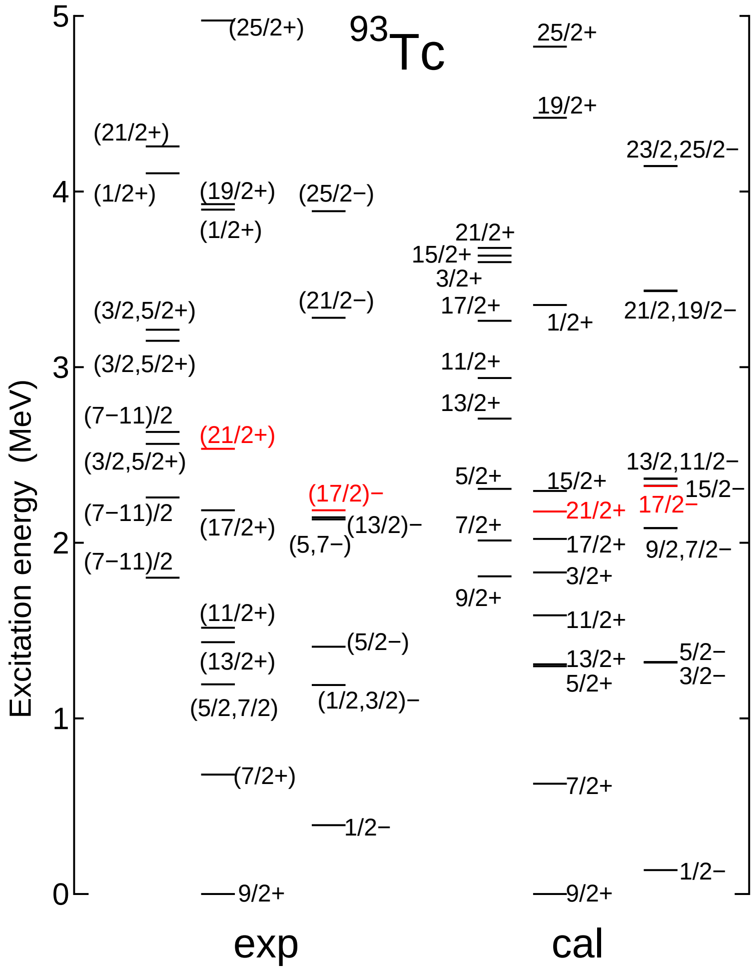

Fig. 2. (Color online) Calculated energy levels of ^{93}Tc, which are compared with experimental data taken from Ref. [14].

Table 2
Structure of the yrast states with spin $1/2^+ < J^\pi \leq 21/2^+$ in ^{93}Tc. The percentage of the main configuration $\pi(p_{1/2})^2(g_{9/2})^3[J^+]$ for each yrast state is shown.

state		state		state		state	
$3/2^+$	89.6	$9/2^+$	82.1	$15/2^+$	91.3	$21/2^+$	93.1
$5/2^+$	84.2	$11/2^+$	92.8	$17/2^+$	92.7		
$7/2^+$	88.8	$13/2^+$	89.2	$19/2^+$	-		

Calculations show that except for the $19/2^+$ and $1/2^+$ states [2] the main component of the yrast states up to $21/2^+$ is of the configuration $\pi(p_{1/2})^2(g_{9/2})^3[J^+]$, the percentage of which is tabulated in Table 2. The isomeric state $21/2^+$ has the single-particle configuration $\pi(g_{9/2})^3[21/2^+]$ as the main structure. The spin 21/2 is attained by alignment of three protons in the $g_{9/2}$ orbit (9/2+7/2+5/2=21/2). The calculation for ^{91}Nb gives the same order of energy levels with respect to spin as in ^{93}Tc. Thus we have understood that the isomeric state $21/2^+$ in the proton-odd nuclei is given by the predominant configuration $\pi(g_{9/2})^3[21/2^+]$.

The difference in the level scheme of ^{93}Mo and ^{93}Tc, especially the inverse order of $21/2^+_1$ and $17/2^+_1$ between the two isotones, is considered to come from the different effects between the np interaction in the coupling $\pi(g_{9/2})^2_8 \otimes \nu d_{5/2}$ and the pp interaction in $\pi(g_{9/2})^2_8 \otimes \pi g_{9/2}$. The long lifetime of the ^{93}Mo $21/2^+$ isomer is thus interpreted as due to the np coupling.

The ^{93}Tc nucleus has another isomeric state $17/2^-$ with lifetime 10.2 μs. Our calculation lays the $17/2^-_1$ state below the $13/2^-_1$ state, in disagreement with the observed order. However, as the difference is small in energy, the obtained wave-function can still be reliable. The calculated $17/2^-_1$ state has 96.5% in the configuration $\pi p_{1/2}(g_{9/2})^4[17/2^-]$. The ^{91}Nb nucleus has a similar level scheme for negative-parity states and an isomeric state with spin $17/2^-$ (lifetime 3.76 μs). Our model reproduces equally well the observed energy levels including the isomeric state $17/2^-_1$. The isomeric state $17/2^-_1$ in both ^{93}Tc and ^{91}Nb has the spin-aligned three-proton configuration $\pi p_{1/2} \otimes \pi(g_{9/2})^2_{8+}[17/2^-]$. The results altogether suggest that the isomeric states in odd-mass nuclei around ^{93}Mo are all characterized by a spin-aligned configuration in which a single neutron or proton couples with a fully aligned proton pair in the $g_{9/2}$ orbit ($(g_{9/2})^2_{8+}$).

The successful calculation for energy levels encourages us to predict electromagnetic transition probabilities for ^{93}Mo, which are relevant to the discussions about the lifetime variation of nuclear isomers in a plasma environment

[2] Because the configuration $\pi(g_{9/2})^3[J^+]$ has no state when J=19/2 and 1/2, the $19/2^+$ and $1/2^+$ states must have the main configuration $\pi(g_{9/2})^5$.

Table 3
Experimental and calculated reduced electromagnetic transition probabilities in ^{93}Mo related to the decay of the isomeric states $21/2^+$ and $17/2^+$. The $B(E4)$, $B(E2)$, and $B(M1)$ values are shown in W.u.

	$B(E4)$ or $B(E2)$		$B(M1)$	
$J_i \to J_f$	exp.	cal.	exp.	cal.
$21/2^+ \to 13/2^+$	1.431 (24)	1.9		
$17/2^+ \to 21/2^+$		3.5		
$17/2^+ \to 13/2^+$	4.48 (23)	4.0		
$19/2^+ \to 15/2^+$		2.5		
$19/2^+ \to 17/2^+$		0.01		0.34
$19/2^+ \to 21/2^+$		0.03		0.84
$15/2^+ \to 17/2^+$		0.02		1.07
$15/2^+ \to 11/2^+_1$		2.2		
$15/2^+ \to 13/2^+$		0.01		0.85
$13/2^+ \to 9/2^+$	417 (93)	7.2		
$9/2^+ \to 7/2^+$		6.5	0.38 (13)	0.47
$9/2^+ \to 5/2^+$	12 (4)	12.9		
$7/2^+ \to 5/2^+$	8.7 (22)	12.6	0.068 (6)	0.037
$3/2^+ \to 1/2^+$		0.51		0.31
$1/2^+ \to 5/2^+$	76^{+75}_{-56}	25		
$3/2^+ \to 5/2^+$		4.9		0.22

[4] and the NEEC effect [5,6]. In Table 3, we show calculated reduced electromagnetic transition probabilities, in which the standard effective charges $e_p = 1.5e$ and $e_n = 0.5e$ for electric transitions are used. For magnetic transitions we employ the quenched spin g-factors $g_p^s = 3.18$ and $g_n^s = -2.18$, which were used in Ref. [16] to explain the observed $B(M1)$ values in ^{94}Mo. As seen in Table 3, all the calculated values of $B(E4)$ or $B(E2)$ as well as $B(M1)$ agree well with the known data. (The experimental value 417 W.u. [14] for $B(E2; 13/2^+ \to 9/2^+)$ is apparently too large, though.) In addition, many unknown transitions are predicted.

The $B(E2)$ values related to the $21/2^+$ and $17/2^+$ states indicate that these isomeric states are not collective, as expected from their fully-aligned configuration $\pi(g_{9/2})^2 \otimes \nu d_{5/2}$. On the other hand, Table 3 indicates a larger collectivity for the low-lying low-spin states. For example, the calculation gives the value $B(E2; 1/2^+ \to 5/2^+) = 25$ W.u. for the observed value 76^{+75}_{-56} W.u, and

therefore, the ground state $5/2^+$ and the first excited state $1/2^+$ are more collective. We stress that our model not only describes the isomeric states $21/2^+$ and $17/2^+$ at high energy but also those low-lying states.

Enhanced decay of the $21/2^+$ isomer in ^{93}Mo, as suggested in Refs. [4,5,6], involves an E2 transition to the upper-lying state $17/2^+$. It is thus crucial to known the E2 transition probability of the $21/2^+$ isomer to the upper-lying state. This transition has not been known experimentally. In the discussion of lifetimes of ^{93}Mo in hot dense plasmas [4], the experimental values of $B(E4; 21/2_1^+ \rightarrow 13/2_1^+)$ and $B(E2; 17/2_1^+ \rightarrow 13/2_1^+)$ were used but the unknown $B(E2; 17/2_1^+ \rightarrow 21/2_1^+)$ value was *assumed* to be the same as $B(E2; 17/2_1^+ \rightarrow 13/2_1^+) = 4.48$ W.u. As shown in Table 3, our model predicts a value 3.5 W.u. for the transition $B(E2; 17/2_1^+ \rightarrow 21/2_1^+)$, which is close to the assumed value in Ref [4]. Although the states are not collective, the predicted $B(E2)$ for the 21/2-to-17/2 transition is quite substantial, and there is therefore a real prospect for observing induced isomer deexcitation suggested by Gosselin *et al.* [4].

In conclusion, using a modern shell model, we have performed microscopic shell model calculations for the ^{93}Mo $21/2^+$ isomer and compared it with the $21/2^+$ and other spin states in the odd-mass nuclei around ^{93}Mo. The calculations have confirmed the conclusion from an early simpler calculation that these isomeric states have rather simple single-particle configurations of 2-proton+1-neutron or 3 protons as the main structure, which are characterized by fully aligned spins. The predominant configuration of the ^{93}Mo $21/2^+$ isomer is $\pi(g_{9/2})^2_{J=8} \otimes \nu d_{5/2}$. We have calculated electromagnetic transition probabilities between the $21/2^+$ isomer and the neighboring states using the detailed shell-model wavefunctions, thus providing the important structure information that has been missing so far in the isomer decay studies. It has been found that the small mixtures of complicated configurations determine the details of the transition probabilities. The long lifetime of the ^{93}Mo isomer is attributed to the fact that the $21/2^+$ state lies below the $15/2_1^+$, $17/2_1^+$, and $19/2_1^+$ states and hence the major electromagnetic transitions $E2$ and $M1$ are prohibited. The predicted E2 transition probability of the isomer to the upper-lying $17/2_1^+$ provides a rather positive support to the proposed enhancement of isomer decay in a plasma environment.

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